BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B 68 12061

SUBJECT: Thoughts on LM Landing Requirements at Science Sites - Case 340

DATE: December 18, 1968

FROM: I. Silberstein

ABSTRACT

An examination of the hardware and software changes that would be necessary to enable a LM landing at science sites has resulted in an attempt to identify the requirements on the LM that would be associated with such a mission.

The landing accuracy must be improved to 1,000 ft radius 3σ. The ΔV budget must be decreased to allow an increase in payload delivery. The guidance system must be able to fly the LM over extremely rough terrain and still enable the astronauts to land safely and accurately.

CSM assistance in Hohmann transfer and in rendezvous will be necessary due to the additional weight of the LM. This will affect the capability of the CSM to do orbital experiments.

The work presented here is at best incomplete. Further work is necessary on the definition of "science missions", mapping of approach terrains to science sites, and mapping of the sites themselves. Only then can the requirements on the LM be better identified.

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MEMORANDUM FOR FILE

INTRODUCTION

LM landing at science sites presents problems which require definition. It is obvious that the landing must be more accurate than in the Apollo landing, that larger payloads must be delivered, and that the approach terrain cannot be selected for smoothness. However, no attempt has been made to define quantitatively the required improvements in the guidance and control system.

An attempt to define the necessary improvements is made in this memorandum. The basic assumption is that the LM must be able to land at sites selected by scientists for their scientific interest, and after landing, the astronaut should be able to perform those tasks which the scientists deem minimal for a successful site exploration.

Another basic assumption is that nowhere should the safety of the astronauts be jeopardized. The "dead man's curve" should not be crossed earlier than it is in an Apollo mission. The astronauts should not fly an LFU to a distance from which they could not walk back unless another LFU is fueled and can be used for rescue.

In any LFU sortie plan the last sortie will not have a back-up for rescue purposes. Thus, the last LFU sortie will have to be restricted to "walk back" range, i.e., to features from which the astronauts may walk back to the LM should the LFU fail. The range limit on such a sortie is not well defined. We will assume that the restriction is due to the life support system. Thus, the first feature visited on the last sortie can be as far as 3 km from the LM. Successive features must be nearer since by then some of the PLSS consumables will have been used.

We assume that the LM active rendezvous capability will not be retained. The additional risks involved will be minor since most modes of failure which would prevent CSM active rendezvous would also prevent Trans Earth Injection.

MISSION STAY TIME

Documents describing particular missions have been published stating the objectives which the scientific community deems desirable. However, the planning work for these missions has been influenced and limited by the extended LM (ELM) capability as it was assumed at the time of planning. These documents leave the impression that the planning work was geared not to the definition of a minimal mission which would justify the risk of expenditure but rather to the efficient use of the assumed ELM capability.

In a sense this approach is reasonable. The missions that scientists would like are limited not by the lack of work to be done at any site but rather by the lack of time, mobility, and scientific instruments. However, this memorandum is concerned with the opposite process of defining the ELM capability required to meet scientific objectives. It is recommended that an ELM mission should be planned by specifying the minimum objectives for a given site, which if they are not met, the decision to fly to that particular site will be reconsidered.

Some previous analyses of ELM capability presented a tradeoff between lunar stay time and payload delivered to the surface. However, this approach does not reflect the real requirements on science missions. The main reason for longer stay time (at least during the lunar exploration phase) is that there are more features to be explored and more instruments to be placed. Thus the tradeoff is not between payload and stay time; both must increase simultaneously. The problem is really to strike a balance between the weight penalties associated with the additional stay time, mobility, and landed instruments.

An existing mission planning document to Hadley Rille[1] calls for 4 EVA's, 3 LFU sorties, 3 days stay time, and 5 km mobility radius. It also recommends an increase in stay time to 4 days. Only two of the LFU sorties may have the 5 km radius; the last LFU flight must be constrained to walk back capability. However, further analysis of the stay time required in the above document reveals that 3 days may not be sufficient. Preliminary operational guidelines permit one EVA on the first and last days on the lunar surface and two EVA's on intermediate days. Preliminary operational guidelines also require some specific activity on the first EVA following landing. The astronauts must first inspect the vehicle, prepare it for ascent, and collect a contingency sample. It will be assumed that they will have sufficient time to deploy and check the two LFU's and prepare them for the first flight on the same EVA.

The second EVA, which must occur on the next day, will consist of an LFU sortie. The whole duration of that EVA will be dedicated to that sortie. When the astronaut returns, however, a second EVA time on that day cannot be used wholly for another sortie since only one LFU is fueled. Thus the next EVA must be utilized for refueling of one LFU, for deployment of ALSEP, and preparation for sample return from all future sorties. That would cut the extra time which must be spent on sample sorting and packaging on the last day.

On the third day the last two LFU sorties may be carried out. Since the very last one is limited to a walk back range, the second astronaut could utilize the EVA time to continue sample return packaging from previous sorties.

After the last LFU sortie is completed, the astronauts would have their rest period. Following that, a short EVA for a last check of the alignment of the ALSEP experiments and last sortie sample packaging is carried out. Ascent follows immediately.

The total stay time is three and one half days. We therefore conclude that a realistic time schedule for a 3 sortie mission is one half day longer than recommended by mission planning exercises.

RADIUS OF OPERATIONS

In most cases the radius of mobility required for science missions is a function of the landing accuracy, or vice versa, the requirement on the landing accuracy is a function of the range of the mobility system. Since the range of the mobility system can be increased only at the cost of additional payload delivery capability to the surface, we prefer to consider the second tradeoff, and to define a landing accuracy requirement which would minimize the mobility needed during the mission. This direction is also imposed by "walking missions" where the landing accuracy is defined by the very limited range of a walking astronaut.

As stated previously, mission planning exercises[(1)] called for a 5 km radius of mobility. However, F. El-Baz[(3)] states that many sites could not be properly explored unless a 10 km range was available. Two examples for an extended range requirement were cited:

1. Dionysius site, where the landing must be executed in the mare and an examination of the crater's rim implies a 10 km mobility radius.

2. South of Alexander, where again the landing must occur in the mare but examination of the highland volcanic area implies a 10 km mobility radius.

A minimum of 50 lbs of samples must be carried back to the ELM. But that is not the limiting factor on the mobility system. The limiting factor is the rescue radius; that is, flight in one direction with one man only and return with two men. D. R. Valley[(4)] estimates the radius of operation of the LFU's mentioned below to be 7.2 km with the rescue mission as a range criterion. He also stated that 400 lbs of fuel would be sufficient (with the same LFU) for a 10 km rescue range.

We assume that only one sortie to 10 km range would be executed, and only the standby, rescue LFU needs that much fuel. In fact it may never have to fly that distance and no additional fuel may be necessary. All that is necessary is the capability, i.e., the tank capacity. Thus there is almost no impact on the required landed payload.

LANDING ACCURACY

Each science site is associated with a number of particular features which must be visited during the mission in order to make it scientifically worthwhile. Two types of missions should be considered:

1. A "walking" mission, where the features of interest are near each other and no mobility aids are necessary (or available) and

2. Missions where the interesting features are dispersed and mobility aids must be used.

In both cases, the dispersion of the features and the mobility of the astronauts (with or without aids) define an area in which the LM must land and yet be able to accomplish the mission. We will refer to that restricted area as the "permissible footprint". However, there is no guarantee that the whole "footprint" will be adequate for landing. Some of the terrain included within the footprint may be too rough for a safe landing. Thus, we must further restrict the landing to the largest area free of dangerous obstacles which is included within the "permissible footprint". This will be called the "landing area".

For the purpose of determination of the required landing accuracy, we assume that the LFU is permitted to range 5 km from the ELM and a walking astronaut only 1.5 km.

A memorandum by D. R. Valley[(5)] includes an analysis of a mission to science site Hadley Rille. The best sortie design leads to a definition of the "permissible footprint" for the mission (Figure 1). The terrain enclosed in this footprint is rough and the largest area of smooth terrain*, near the center of the "footprint", is approximately 1,000 ft in radius.

A walking mission to the ledge on the northern wall of Copernicus was analyzed and the features of interest determined.[(6)] A "permissible footprint" can be defined as that area which is within 1.5 km of each of the features of interest. The farthest features on the ledge are approximately 2 km apart. That defines a "footprint" with a radius of only .5 km or 1,700 ft (Figure 2).

If the walking range is only 1 km, the mission will have to be reevaluated, aided by an LFU, or the landing accuracy restricted to a very small radius.

Photographs of the area around a site in the Schröter's Valley area[(6)] were inspected with reference to an approximate LFU sortie analysis. The terrain in the "footprint" was found to be rough and no circle larger than 1,000 ft radius of smooth terrain could be found (Figure 3).

To summarize, an error circle of 1,000 ft radius 3σ should be considered as acceptable for science missions unless rigorous analysis of the terrain roughness shows that the radius should be restricted further.

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*The landing area was chosen by inspecting Orbiter V high resolution photography. No analysis was made. The only criterion was that the landing area appeared smooth enough for landing.

PAYLOAD DELIVERY CAPABILITY

The payload delivery capability of the ELM should really be the output of all the tradeoffs associated with landings at science sites. It is a function of the mission profile, ascent and descent trajectories, and lunar stay time, and is governed by the amount of fuel available in the descent and ascent stages of the ELM. In the following study, however, the payload necessitated by a typical science mission is determined first, implying the ΔV available for the descent and ascent maneuvers. The assumption is that a trajectory satisfying the ΔV constraints will be developed.

The following assumptions will be made:

1. The lunar stay time of a "science mission" is 3.5 days. Stay time may be traded off against delivered payload.
2. Two Lunar Flying Units (LFU's) must be landed.
3. Fuel sufficient for two "long range" sorties and one "short range" must be provided. The "short range" sortie implies that there will be no need for rescue capability during the last sortie and thus only three LFU propellant charges must be provided.
4. Life support for an additional 2.0 days stay imposes a weight penalty of 350 lbs (total stay time 3.5 days).
5. Science payload for advanced ALSEP is 420 lbs.
6. CSM active rendezvous will become the primary mode of operation.
7. The LM will be delivered to a circular orbit 50,000 ft above the surface, a saving of $\sim$ 140 fps.
8. No engine improvement is assumed. (Tradeoffs between the ΔV budget and engine Isp improvements will be summarized later.)
9. No savings in LM weight will be possible.
10. The first 300 lbs of fuel residuals are not usable for LFU flight.
11. The ascent stage will carry an additional 120 lbs of lunar samples and film to orbit.

12. An additional 125 lbs of equipment in the form of hoses for fuel residual transfer, additional sample return containers, etc. will be carried to the lunar surface.

The total additional weight which must be delivered to the Moon is 1,595 lbs. The breakdown is as follows: two LFU's - 400 lbs, fuel for the LFU (assumed loaded in their tanks) 600 lbs, stay time extension 350 lbs, additional equipment 125 lbs. Since 300 lbs are already provided for science payload, only 210 lbs are added to the weight penalty.

On the other hand, 270 lbs of RCS fuel are saved by CSM active rendezvous. However the net inert weight saving to the ascent stage is only 150 lbs since an additional 120 lbs of lunar samples and film are added prior to lift off. There is also a saving of 130 lbs of ascent fuel resulting from the inert weight savings. Thus the ascent stage is 400 lbs lighter when delivered to the lunar surface, and the ELM is 1,195 lbs heavier than the Apollo system.

The total maximum weight of fuel and oxidizer loaded on the LM descent stage is 17,969 lbs.[7] Assuming that 300 lbs of the residuals are unusable and that the fuel needed for the last sortie is 300 lbs, we postulate the landed fuel weight left as residuals to be 600 lbs. That leaves 17,370 lbs for the powered descent maneuver. The initial LM weight is 34,520 lbs and its descent engine Isp is 299.4 seconds.

An increase in engine Isp of 1 second provides an additional 20 ft/sec ΔV for the powered descent or approximately 70 lbs increase of the initial LM weight or approximately 50 lbs fuel saving (transferable to the LFU). Each ft/sec saved in the powered descent will allow 3.2 lbs increase in the initial LM weight.

TERRAIN - TRAJECTORY REQUIREMENTS

Despite a large number of simulations of the Apollo trajectory, no definite criteria were established for the maximum allowable pitch variations or radar data loss. Therefore there is no simple way to define the requirements on the trajectory - terrain interaction for science sites. In addition, the rationale for the existing requirements on the visibility phase is rather vague and may have to be reevaluated.

Thus we shall attempt to define the guidance system through a set of requirements on its performance, i.e., by demanding a certain degree of insensitivity of the trajectory to the terrain under it. We will first define what tests the trajectory must be able to pass; and then, the type of terrain to which it must be insensitive.

The trajectory must have the following characteristics:

1. The dead man's curve will not be crossed until the LM is approximately 200 ft uprange of the landing site.

2. The LM must be able to land within 1,000 ft of the nominal touchdown point.

3. The trajectory will permit safe landing within the required ΔV budget.

4. The visibility phase must allow:

    a. Visual assessment of the safety of the trajectory sufficiently early for abort to be carried out; and

    b. short range inspection of the landing site which should be well outside the washout region. The visibility phase must last long enough for an accurate redesignation to take place. If visibility is intermittent, there must be a second period during which the results of the first redesignation can be checked and corrected.

During the flight, the guidance system must be able to fly the LM over the type obstacles detailed below, superimposed upon a 1° slope uncertainty:

1. Pass over a 4,000 ft drop 10 km uprange from the landing site. (Hadley Rille - Figure 1)

2. Pass over a 1,500 ft deep crater whose near rim is 8 km from the landing site. (Hyginus Rille - Figure 4)

3. Fly over an average slope of 4% for the last 10-15 km of the trajectory. (Schroter's Valley - Figure 5)

4. Pass over a drop of 2,500 ft <u>anywhere</u> from 5 to 18 km from the landing site. (Copernicus, northern wall - Figure 6)

These obstacles must be overflown with any reasonable combination of initial conditions and IMU errors, DPS and slope uncertainties, without violating the safety, accuracy, ΔV and visibility constraints.

The problems associated with these obstacles may become more severe in the context of the terrain variations preceeding or following it. However, since the analysis of the terrain for science sites has not been carried out, there is no way at present to more accurately specify the requirements on the guidance system.

CONCLUSIONS

The work presented here is at best incomplete and provides only a rough indication of the guidance and navigation problems associated with LM landing at science sites.

The author proposes that an approximate reduction of lunar photographs of the science site areas and the approach terrain to them be carried out as soon as possible. This work would enable the determination of the exact landing areas in each science site, and the terrain-trajectory interaction when approaching it. This in turn would aid in defining an exact set of requirements on the guidance and navigation system.

Further work is also necessary on the definition of "walking mission" range and the permissible range of the last LFU sortie.

The ELM capability requirements as stated above are in a sense functions of the assumed ELM capability. There is a definite need for replanning a typical ELM mission basing it not on assumed ELM capability but on the minimal scientific objectives. Only then will it be possible to rationally plan the requirements on ELM landing.

The additional weight of the ELM and the additional burns the CSM must perform to deliver the ELM to a 50,000 ft circular orbit and to rendezvous will seriously affect the capability to do orbital experiments. This is especially so since the critical shortage is probably in CSM RCS fuel, and the above mentioned maneuver may have to be performed with the RCS. The answer may be found by stressing the CSM capabilities on some missions and the ELM's capability on others.

Ilan Silberstein

2015-IS-acm I. Silberstein

Attachments
References
Figures 1 - 6

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4. D. R. Valley, Bellcomm, Inc., personal communication.

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6. "Geologic Characteristics of the Nine Lunar Landing Mission Sites Recommended by GLEP", TR-68-340-1, F. El-Baz, May 31, 1967.

7. "A New Look at LM Descent Budget", MSC Memo No. 68-FM71-245, M. D. Cassetti/FM7, May 27, 1968.

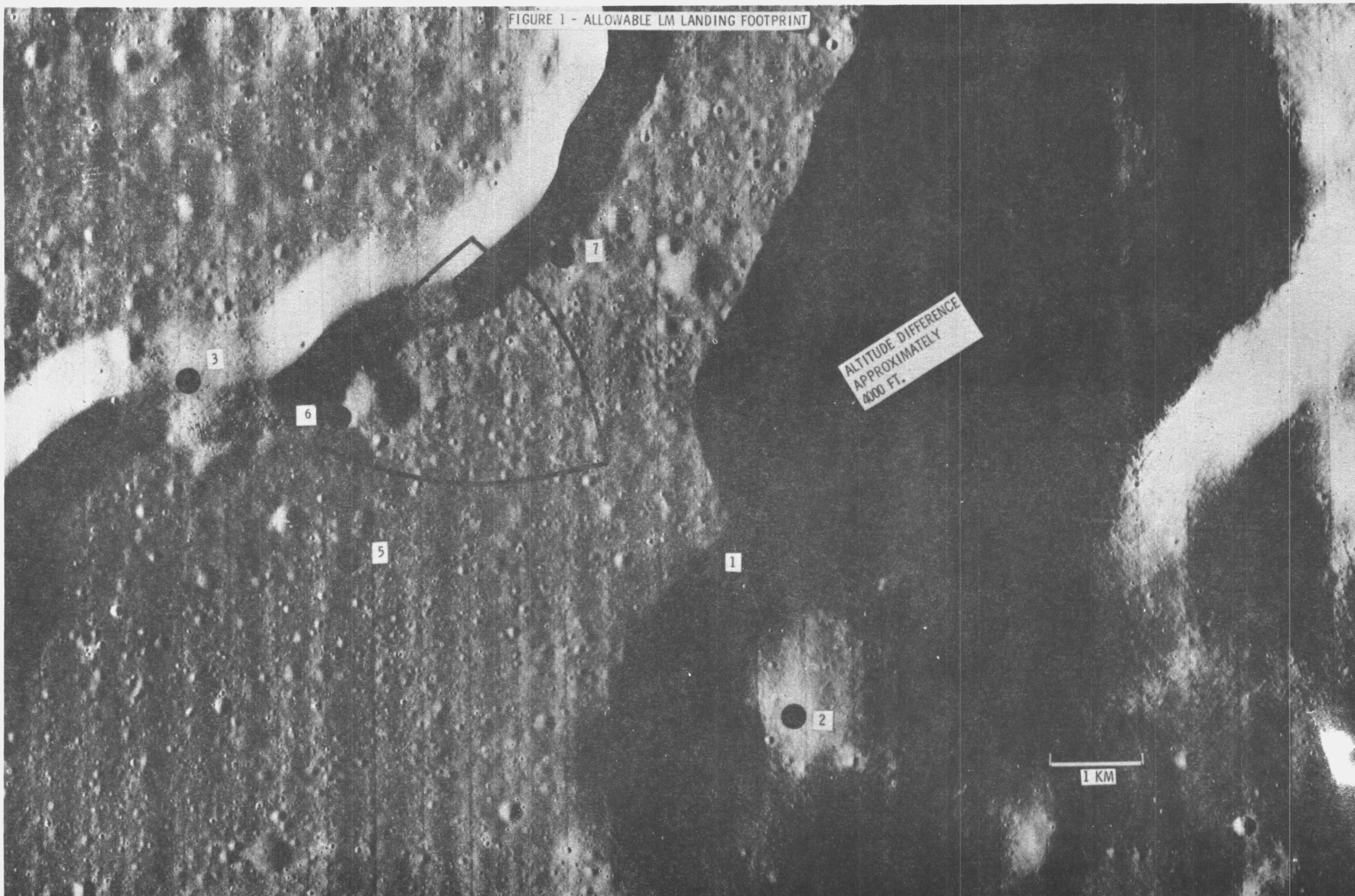


FIGURE 1 - ALLOWABLE LM LANDING FOOTPRINT
7
3
6
5
1
2
ALTITUDE DIFFERENCE
APPROXIMATELY
4000 FT.
1 KM

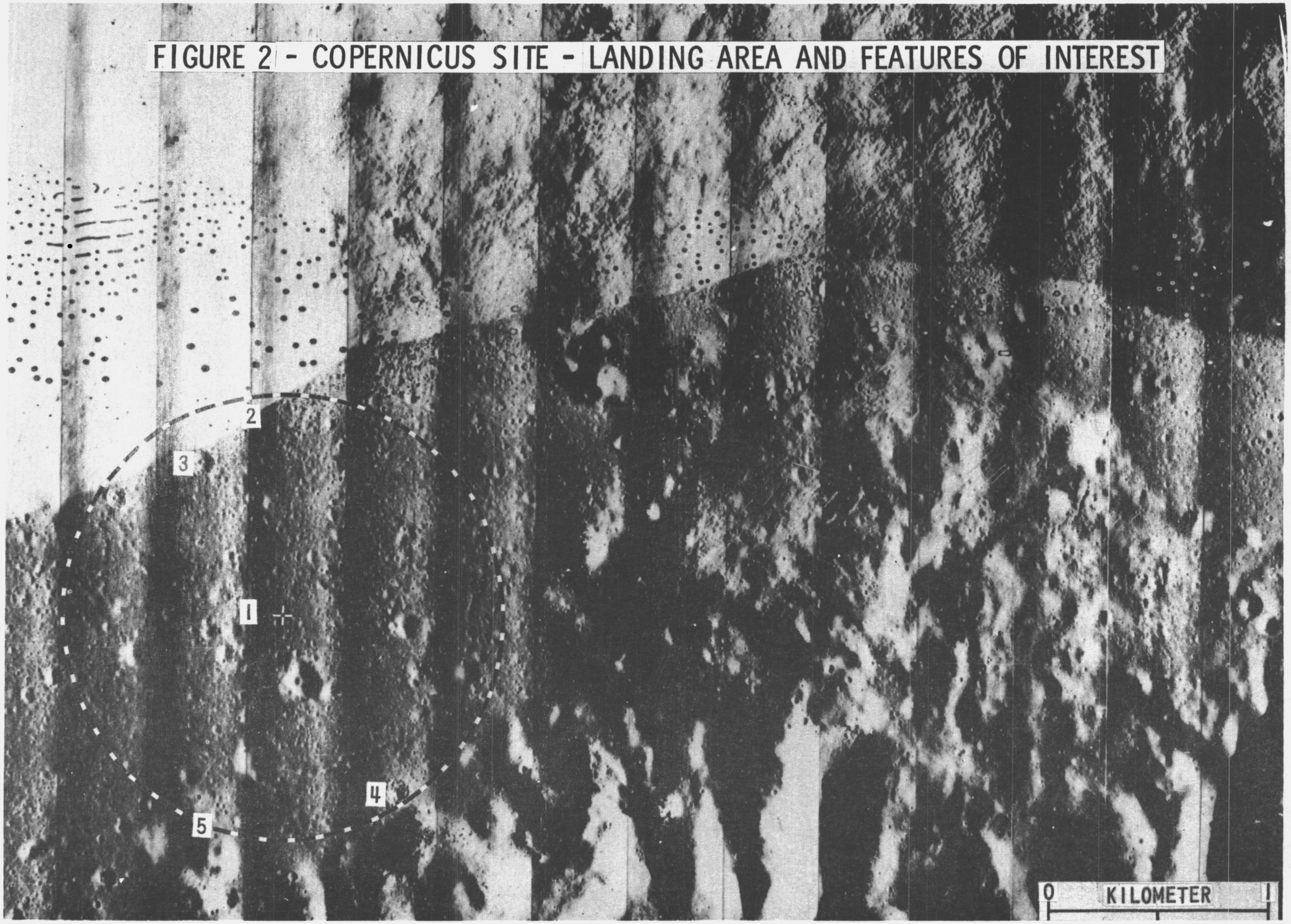
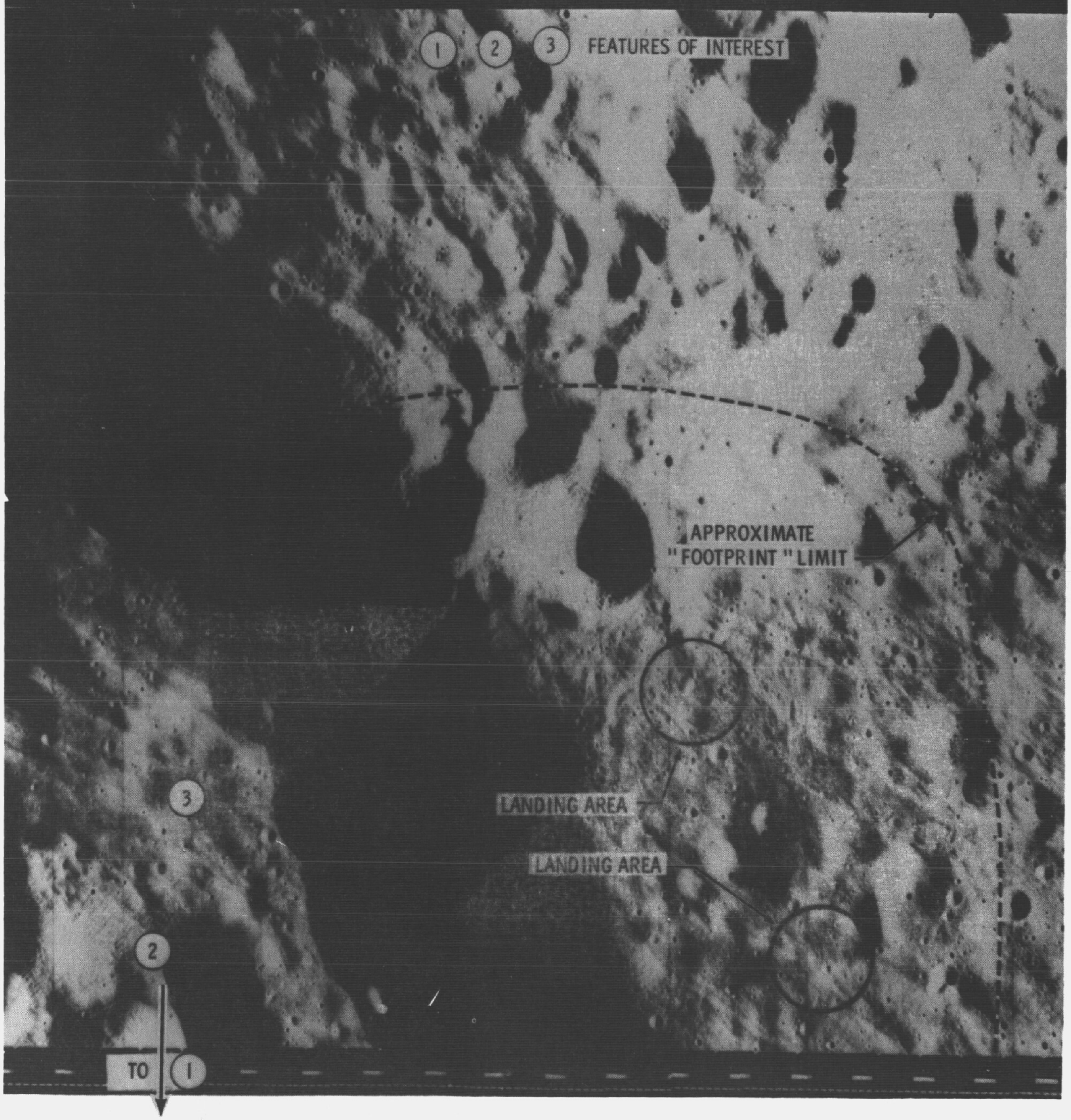


FIGURE 2 - COPERNICUS SITE - LANDING AREA AND FEATURES OF INTEREST
1
2
3
4
5
0 KILOMETER 1

FIGURE 3 - SCHROTER'S VALLEY SITE



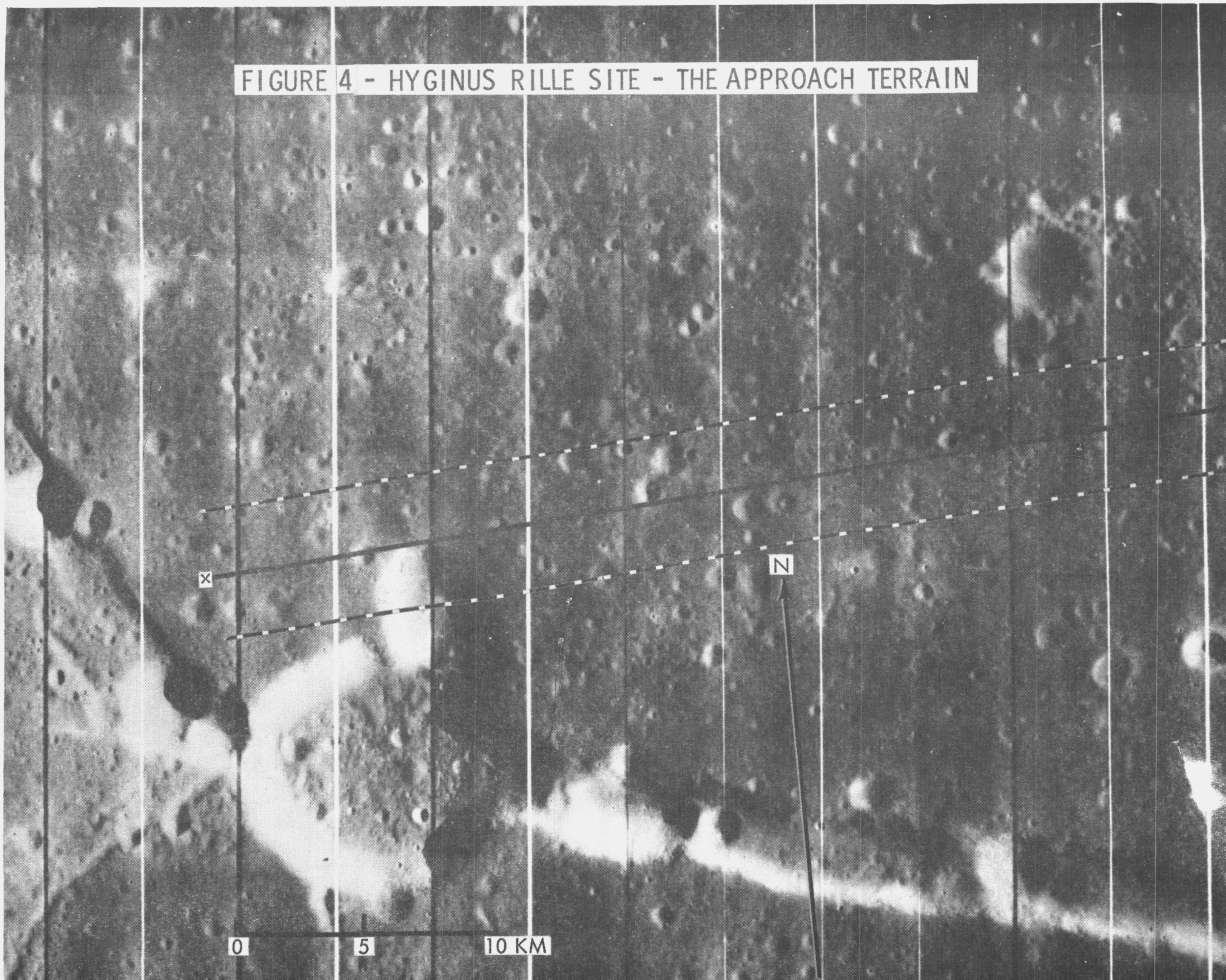


FIGURE 4 - HYGINUS RILLE SITE - THE APPROACH TERRAIN
X
N
0
5
10 KM

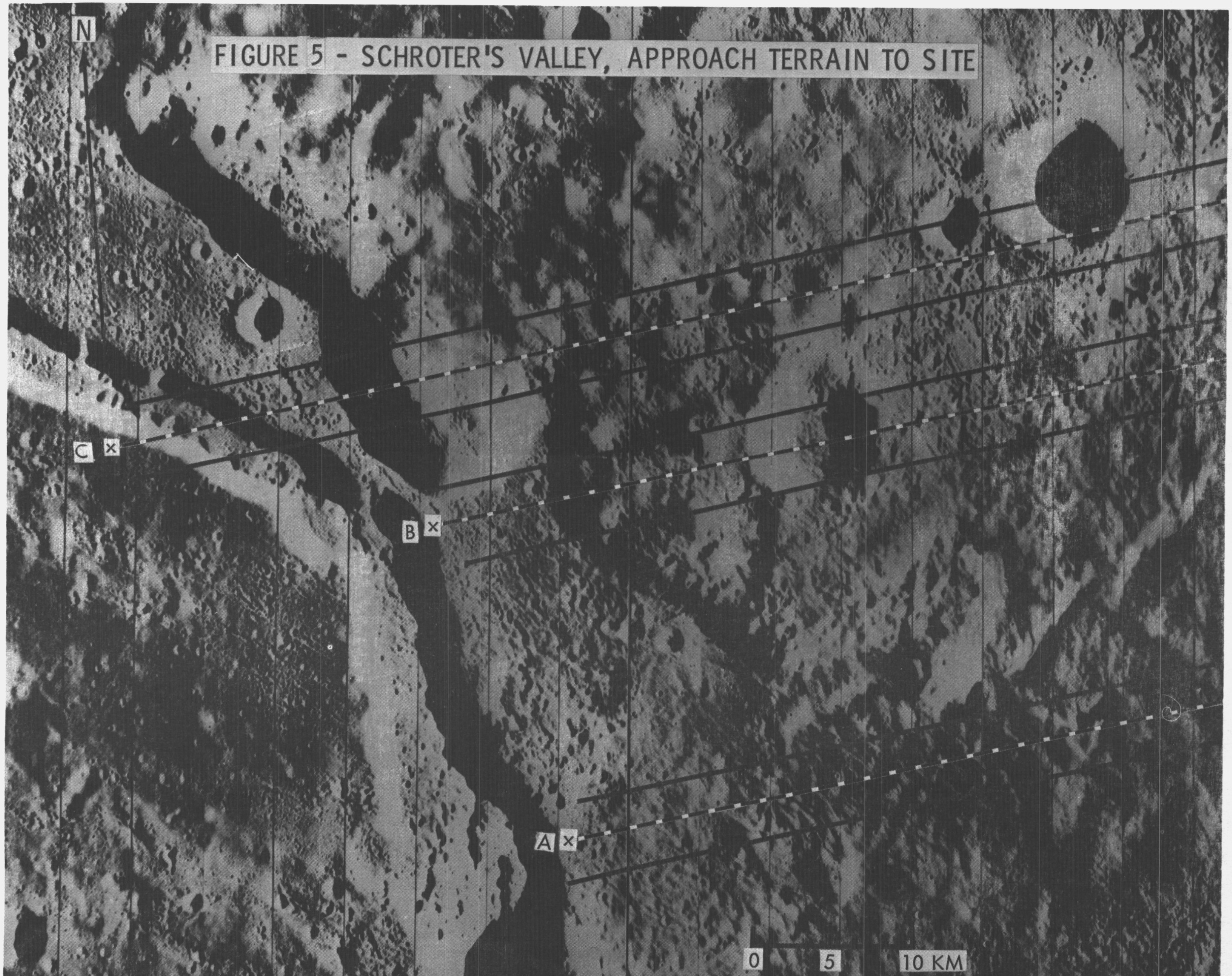


FIGURE 5 - SCHROTER'S VALLEY, APPROACH TERRAIN TO SITE

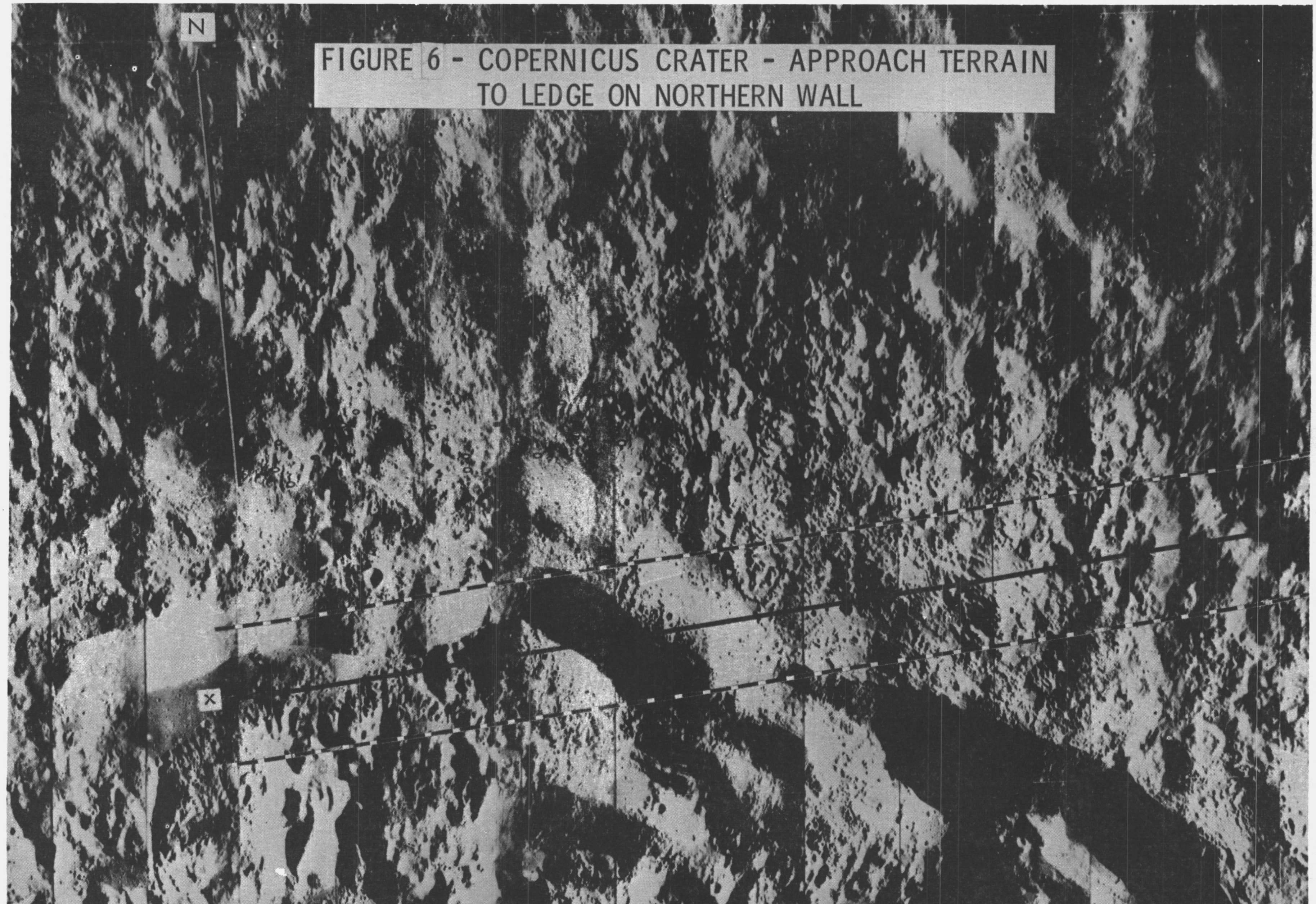


FIGURE 6 - COPERNICUS CRATER - APPROACH TERRAIN TO LEDGE ON NORTHERN WALL